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Holocene Climate Inferred from Oxygen Isotope Ratios in Lake Sediments, Central Brooks Range, Alaska

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Analyses of sediment cores from two lakes in the central Brooks Range provide temperature and moisture balance information for the past ∼8500 cal yr at century-scale resolution. Two methods of oxygen isotope analysis are used to reconstruct past changes in the effective moisture (precipitation minus evaporation) and temperature. Effective moisture is inferred from oxygen isotope ratios in sediment cellulose from Meli Lake (area ∼0.13 km^2, depth 19.4 m). The lake has a low watershed-to-lake-area ratio (7) and significant evaporation relative to input. Summer temperature shifts are based on oxygen isotope analyses of endogenic calcite from Tangled Up Lake (area ∼0.25 km^2, depth 3.5 m). This basin has a larger watershed-to-lake-area ratio (91) and less evaporation relative to input. Sediment oxygen isotope analyses from the two sites indicate generally more arid conditions than present prior to ∼6000 cal yr B.P. Subsequently, the region became increasingly wet. Temperature variability is recorded minimally at centennial scale resolution with values that are generally cool for the past ∼6700 cal yr. The timing and direction of climate variability indicated by the oxygen isotope time series from Meli and Tangled Up lakes are consistent with previously established late Holocene glacier advances at ∼5000 cal yr B.P. in the central Brooks Range, and high lake-levels at Birch Lake since ∼5500 cal yr B.P. This unique use of oxygen isotopes reveals both moisture balance and temperature histories at previously undetected high-resolution temporal scales for northern Alaska during the middle to late Holocene.

Key Words: **Alaska; Holocene; paleoclimate; Brooks Range; lake sediments; δ^{18}O; cellulose; *Chara*.**

INTRODUCTION

Geomorphological evidence of late Holocene glacial advances in the central Brooks Range of northern Alaska suggests that the region has been sensitive to changes in temperature and effective moisture balance (Ellis and Calkin, 1979, 1984; Hamilton, 1986; Calkin, 1988). However, the lichenometry-based chronology of these events only provides an approximate minimum age for glacial retreat. Furthermore, the study sites, being limited to high mountain environments, do not closely define the spatial extent and magnitude of the climatic shifts.

Holocene climatic changes at millennial time scales have been inferred from pollen records in northern Alaska (Eisner and Colinvaux, 1992; Anderson and Brubaker, 1993, 1994; Edwards and Barker, 1994), ostracode trace-element geochemistry (Hu *et al.*, 1998) in southwestern Alaska, and lake-level reconstructions in interior Alaska (Abbott *et al.*, 2000; Figs. 1 and 6). We analyzed oxygen isotopes in multiple sediment cores from Meli, and Tangled Up lakes (Fig. 1), located on opposite sides of the Brooks Range, to improve the detail and resolution of the current climatic history. These lake basins have strong contrasts in hydrology and sedimentology, thereby allowing us to take advantage of the multi-proxy nature of the oxygen isotope data to produce a unique climatic history that includes both effective moisture balance and temperature. The analytical precision of the geochemical data and the chronology are of sufficient quality in these new sites to document Holocene climatic variability at millennial-to-centennial time scales.

PALEOCLIMATIC APPLICATION OF LAKE SEDIMENT OXYGEN ISOTOPES

The oxygen isotope ratio of lake water is influenced by watershed hydrology and is closely linked to local climatic conditions. Lake-water oxygen isotopic composition is controlled by: (1) the combined isotopic composition of input waters from catchment runoff, precipitation falling directly into the lake, and groundwater inflow and (2) evaporative enrichment caused by preferential evaporation of the lighter ^{16}O isotope in water molecules. Open lake systems that have a large catchment area relative to their lake surface area typically have a low evaporation to inflow ratio (E/I). Consequently, the δ^{18}O of lake water is controlled by the δ^{18}O of input waters. In northern latitudes, a strong correlation exists between temperature and the δ^{18}O of precipitation (Dansgaard, 1964; Rozanski *et al.*, 1992). Therefore, the

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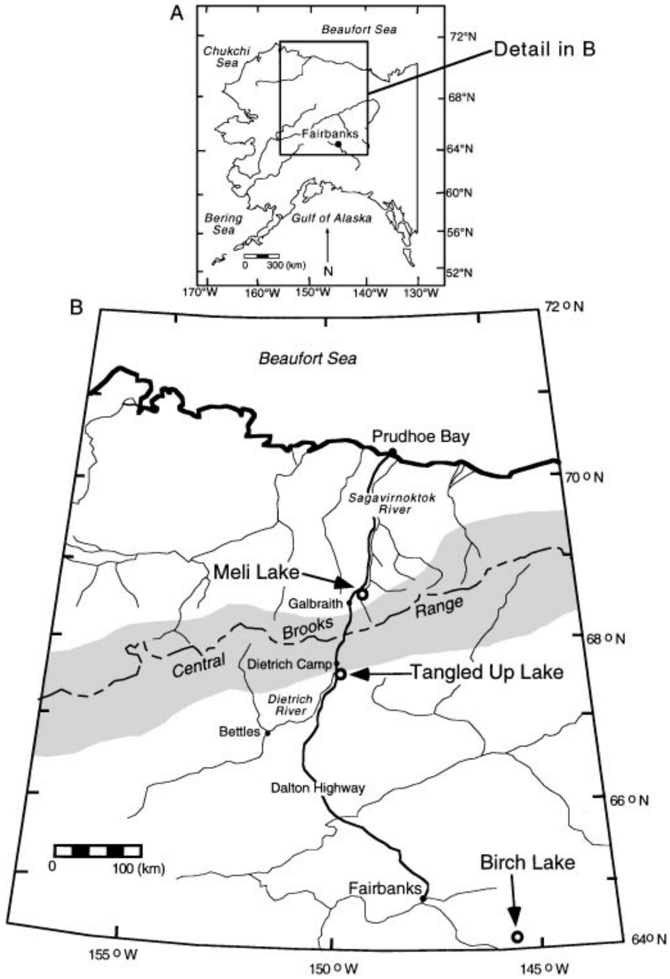

FIG. 1. Location of study area and Meli, Tangled Up, and Birch lakes (modified from Haugen, 1982). The shaded area represents elevations >400 m in the Brooks Range.

oxygen isotopic composition of lake water is considered a proxy for mean summer temperature. In contrast, open lake systems that have a small catchment area relative to their lake surface area have a higher E/I ratio, and the δ^{18}O of lake water is more strongly influenced by evaporative effects. For these systems, the oxygen isotopic composition of lake water is a proxy for effective moisture. Increased evaporation rates cause ^{18}O-enrichment in the lake water, whereas decreased evaporation causes ^{18}O-depletion. Depending on the lake system, lake-water δ^{18}O is more sensitive to either effective moisture or summer temperature.

The moisture balance history of lake water that is isotopically modified by evaporation can be determined from oxygen isotope ratios of sediment cellulose (Edwards and McAndrews, 1989; MacDonald *et al.*, 1993; Wolfe *et al.*, 1996). Ratios in aquatic cellulose are consistently enriched by 27 to 28‰ (±3‰) compared with water values and are unaffected by changes in temperature, $p\mathrm{CO}_2$, or species effects (Epstein *et al.*, 1977; DeNiro and Epstein, 1981; Sternberg, 1989; Yakir, 1992). Gibson *et al.* (1996) tested the use of isotopic techniques for estimating evaporation in a small, shallow tundra lake in the continental Canadian Arctic by comparing results with those from standard methods of mass and energy balances, aerodynamic profile, and evaporation pans. Overall, the isotope and standard methods were found to be in good agreement. These results support the assertion that lake-water isotopic composition in lakes with high evaporation to inflow ratios, such as Meli Lake, is primarily controlled by effective moisture.

Oxygen isotope ratios of endogenic carbonate (*Chara* sp., calcite stem encrustations) can be used to document temperature variations. Charophytes are macroscopic algae that provide a locus and kinetic advantage for the precipitation of calcite during photosynthesis (bio-induced calcification). The extracellular calcite is integral but not essential to the photosynthetic process (McConnaughy, 1991; McConnaughy and Falk, 1991). If lake water is in isotopic equilibrium with endogenic carbonate, calcite encrustations preserved in the lake sediment contain an oxygen isotopic ratio that depends on the oxygen isotope composition and temperature of the lake water. Some research suggests that with the onset of eutrophication, *Chara* calcite has equilibrium values that are more negative than expected (Huon and Mojon, 1994; Fronval *et al.*, 1995). However, measurements from temperate lakes with short residence-time indicate that *Chara* calcite has accurately recorded post-glacial warming, Younger Dryas cooling, and the Pre-Boreal Oscillation (Drummond *et al.*, 1995; Yu and Eicher, 1998).

Chara calcite encrustations are most likely in equilibrium with lake-water δ^{18}O in Tangled Up Lake because it is shallow, oligotrophic, and well mixed. Isotopic modification of input sources is probably minor in the lake's hydrologically dynamic enviroment. In such cases lake-water isotopic composition is essentially equivalent to atmospheric input, and qualitative summer atmospheric temperature variability can be reconstructed by accounting for the lake-water temperature fractionation factor (Yu *et al.*, 1997; Yu and Eicher, 1998; Von Grafenstein *et al.*, 1999).

STUDY SITES

The two study sites were selected because of the contrating characteristics of their lake sediments and watersheds. Meli Lake (68° 41′ 01″ N, 149° 04′ 30″ W, 741 m) and Tangled Up Lake (67° 40′ 00″ N, 149° 04′ 30″ W, 440 m) (both informal names) are on the northern and southern slopes of the Brooks Range, respectively (Fig. 1). Meteorological data (1975–1978) show that rainfall accounts for approximately two-thirds of the precipitation at Dietrich Camp, 1 km north of Tangled Up Lake, and Galbraith, 12 km west of Meli Lake (Haugen, 1982; Fig. 1). Totals are less than ∼450 mm/yr and ∼270 mm/yr for each area (Haugen, 1982). Tangled Up Lake is on average slightly warmer (∼1°C mean annual air temperature, MAAT) than Meli Lake (∼0°C MAAT; Haugen, 1982).

Meli Lake is 19.4 m deep with a surface area of ∼0.13 km^2. It has a modest-sized (0.91 km^2) watershed with a watershed-to-lake-area ratio of 7. The lake has one small outflow and no surface stream inflow. It is perched on the crest of a broad 180-to-245-m-high lateral moraine that flanks the west side of the Sagavirnoktok River valley (Hamilton, 1986). *Betula* shrub tussock tundra surrounds Meli Lake. We estimated that the E/I ratio is ~0.44 based on thaw season estimated evaporation (260 mm/yr), evapotranspiration (186 mm/yr), a precipitation estimate at Galbraith of 270 mm/yr (Haugen, 1982), catchment basin size, and the lake area. The relatively high E/I ratio suggests that $\delta^{18}O$ increases in lake water are due to evaporation, whereas decreases are caused by greater effective moisture.

Tangled Up Lake is 3.5 m deep, and has a surface area of ~0.25 km^2. The basin has a large watershed (22.6 km^2), with a watershed to lake area ratio of 91. The lake is located 600 m east of the Dietrich River, between 15 to 30 m above the modern river level, and lies within the *Picea* forest limit. Successive glacial advances during the Pleistocene scoured the Dietrich River valley. Maximum ice extent occurred as far as 35.2 km down-valley of Tangled Up Lake during the most recent glaciation ((Itkillik II) 12,500–13,000 ^{14}C yr B.P.; Hamilton, 1986). We calculated an E/I ratio of ~0.019 using the same criteria as for Meli Lake, plus a measured average precipitation total of 418 mm/yr at Deitrich Camp (Haugen, 1982). This relatively low E/I ratio suggests that the isotopic composition of lake water at this location is dominated by atmospheric precipitation and ultimately by atmospheric temperature.

METHODS

Cores were collected from a floating platform during summer 1998, with a modified square-rod piston corer (Wright *et al.*, 1984). A gravity corer (Glew, 1988) was used to collect undisturbed sediment–water interface and upper-core samples. The Meli Lake core ended in impenetrable gravel. Coring was stopped at Tangled Up Lake by the mechanical and physical limitations of the coring device after penetrating 8.6 m of clay below the 3.5-m-long sediment record presented here. The Meli Lake data are a composite of two piston cores (cores A and C) and gravity core. The Tangled Up Lake data were obtained from a single piston core (core B).

A Bartington Susceptibility bridge set to low frequencies measured magnetic susceptibility. Loss on ignition (LOI) was calculated following Bengtsson and Enell (1986). Total carbon (TC) and total organic carbon (TOC) were measured for selected samples with a Leco Coulometric System. Core lithology was determined by smear slide mineralogy, x-ray diffraction, and visible inspection of sediment features, including Munsell color, textures, sedimentary structures, and biogenic features.

Sediment cellulose and aquatic macrophyte extraction procedures followed Wolfe *et al.* (1996). Carbon dioxide from sediment cellulose samples was extracted using a modified nickel tube pyrolysis method (Edwards *et al.*, 1994; Thompson and Gray, 1977). The $^{18}O/^{16}O$ ratios of the sediment cellulose were determined on a Finnigan MAT Delta E mass spectrometer. Analytical precision for pure cellulose standard analyses was 0.4 to 0.6‰ (Anderson, 1999). Duplicate analysis for Meli Lake sediment cellulose showed precision of 0.01 to 2.17‰. $^{18}O/^{16}O$ ratios of calcite from sediment samples were analyzed on more than five individual *Chara* stem encrustations per sample. The stems (~1 to 2 mm each in length) were treated with a 50% bleach solution for 5 hours, rinsed until neutral, ground into a fine powder, subsampled, and analyzed. Duplicate analyses were carried out on select samples and individual stems to assess variations. Sample reproducibility is approximately ± 0.5‰. Elemental carbon, nitrogen, and $^{13}C/^{12}C$ ratios were analyzed on acid pretreated samples by a Europa 20/20 mass spectrometer. Analytical precision for bulk organic $\delta^{13}C$ and calcite $\delta^{18}O$ was better than ± 0.1‰. All isotope results are reported in δ-notation ($\delta = ([R_{sample}/R_{standard}] - 1) \times 1000$, where $R = {}^{18}O/{}^{16}O$ or $^{13}C/^{12}C$) and are expressed as per mil (‰) relative to the international standards: Peedee Belemnite (VPDB) for bulk organic $\delta^{13}C$ and calcite $\delta^{18}O$, and Vienna standard mean ocean water (VSMOW) for cellulose $\delta^{18}O$.

Core chronologies are based on ^{210}Pb analyses and AMS radiocarbon dating of identifiable macrofossils (Table 1). Terrestrial macrofossils were not present in sufficient quantities for radiocarbon measurements at many stratigraphic levels. Therefore, intact aquatic bryophyte macrofossils or sieved microscopically identifiable aquatic plants were used. Both measured radiocarbon and calibrated ages are reported, but only calibrated ages are used for discussion. Radiocarbon ages were calibrated using INTCAL98 (Stuiver *et al.*, 1998). ^{210}Pb activity for Tangled Up Lake was measured on 0.5- to 1.0-cm thick sediment slices taken in the laboratory from a polycarbonate-barrel piston interface core. The Meli Lake gravity core samples used in ^{210}Pb dating were extruded in the field in 0.5- or 1.0-cm slices (Glew, 1991). The constant rate of supply (CRS) model was used to determine ^{210}Pb ages (Appleby and Oldfield, 1978).

An age model for Meli Lake was constructed using 20 ^{210}Pb measurements and 6 radiocarbon ages. An anomolously old radiocarbon age from sieved organic material at 16.5-cm depth was excluded. A linear interpolation between dated depths above and below the sediment cellulose sample depths was used to determine ages. All sample ages below 126 cm are extrapolated from the slope between the data points at 108 to 126 cm.

An age model for Tangled Up Lake was constructed using 10 ^{210}Pb measurements and 9 radiocarbon ages. A 980-yr reservoir age-correction was determined from the difference between the extrapolated ^{210}Pb age and the 1230 ± 70 ^{14}C yr B.P. (CAMS 51359) date at 10 cm. The reservoir correction was applied to all ages above the uppermost depth of the laminated silt unit at 120 cm. Ages of 3170 ± 50 ^{14}C yr B.P. (CAMS 43667) from a wood fragment and 3200 ± 35 ^{14}C yr B.P. (OS 17692) from sieved aquatic macrophyte material at 171 cm were statistically identical and indicate little or no reservoir effect below the upper carbonate-rich unit. Four ages were excluded from the age model, because they do not fit the age–depth slopes established

TABLE 1
AMS Radiocarbon Dates from Meli Lake and Tangled Up Lake

Lake[a]	Depth (cm)	Material	Measured age (^{14}C yr B.P.)	Reservoir corrected age (^{14}C yr B.P.)	Median calibrated age (cal yr B.P.)	Lab #
Meli Lake	16.5	Sieved organic material	2240 ± 60		2230[b]	OS-18370
Meli Lake	27	Aquatic bryophyte	1210 ± 110		1110	OS-18372
Meli Lake	62	Aquatic bryophyte	3130 ± 70		3430	OS-19811
Meli Lake	73	Aquatic bryophyte	3700 ± 60		4030	OS-18374
Meli Lake	86	Aquatic bryophyte	4010 ± 60		4490	OS-18375
Meli Lake	108	Aquatic bryophyte	5640 ± 180		6410	OS-18377
Meli Lake	126	Aquatic bryophyte	6710 ± 50		7540	CAMS-43669
Tangled Up Lake	10	Aquatic macrofossil	1230 ± 70	250 ± 70	290	CAMS-51359
Tangled Up Lake	27	Aquatic macrofossil	1590 ± 55	610 ± 55	610	OS-18362
Tangled Up Lake	32	Aquatic macrofossil	1750 ± 100	770 ± 100	670	OS-18361
Tangled Up Lake	40	Aquatic macrofossil	1680 ± 70	700 ± 70	660[b]	CAMS-51349
Tangled Up Lake	58.5	Aquatic macrofossil	1430 ± 50	450 ± 50	510[b]	OS-18363
Tangled Up Lake	60	Aquatic macrofossil	2340 ± 40	1360 ± 40	1290	CAMS-51348
Tangled Up Lake	94	Aquatic macrofossil	3030 ± 70		3210[b]	CAMS-51340
Tangled Up Lake	136.5	Aquatic macrofossil	3030 ± 70		3210	CAMS-51351
Tangled Up Lake	171	Wood	3170 ± 50		3370	CAMS-43667
Tangled Up Lake	171	Aquatic macrofossil	3200 ± 35		3390[b]	OS-17692
Tangled Up Lake	240	Aquatic macrofossil	4010 ± 55		4490[b]	OS-17693
Tangled Up Lake	287.5	Aquatic macrofossil	3690 ± 100		4040	CAMS-51352
Tangled Up Lake	308	Aquatic macrofossil	4290 ± 70		4850	CAMS-51353
Tangled Up Lake	320	Terrestrial macrofossil	5000 ± 50		5730	CAMS-43668

[a] Meli Lake samples from core C, Tangled Up samples from core B.
[b] Not used in age model.

by the radiocarbon and ^{210}Pb dates. A linear interpolation was used to compute ages between dated depths above and below the calcite sample depths. All sample ages below 320 cm are extrapolated from the slope between data points at 308 and 320 cm.

RESULTS

Meli Lake

Meli Lake sediment did not contain any calcite. High magnetic susceptibility and low LOI characterize the basal gravel

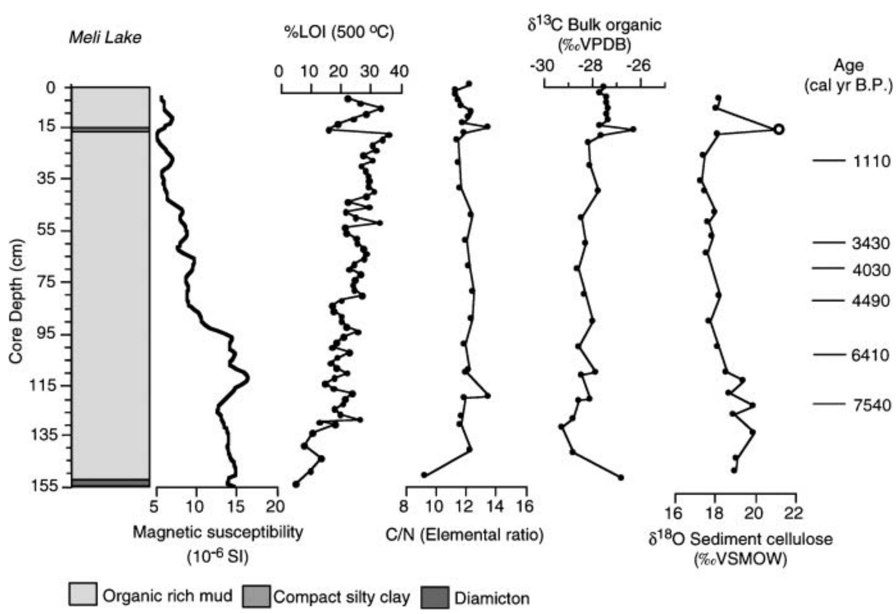

FIG. 2. Core lithology, physical and geochemical properties including magnetic susceptibility, LOI, C/N ratio, δ^{13}C of bulk organic sediment, δ^{18}O of sediment cellulose (average of one to three measurements), and median calibrated radiocarbon ages for Meli Lake. The hollow circle represents the 16.5-cm sediment cellulose sample considered to be contaminated by reworked material.

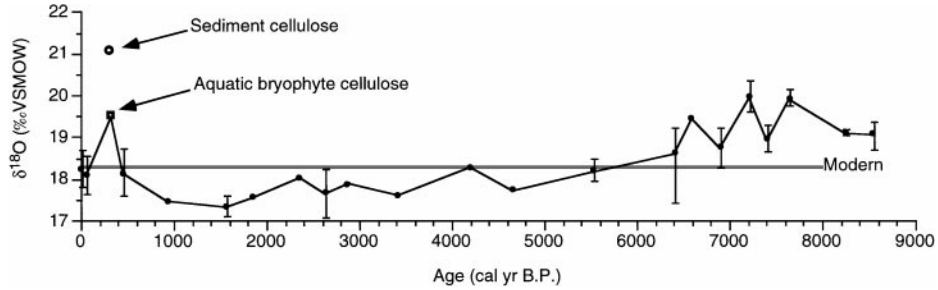

FIG. 3. Time series of Meli Lake sediment cellulose $\delta^{18}O$. Error bars indicate ranges of duplicate or triplicate analyses. Horizontal line is extended from the value of the uppermost sample at 2-cm depth. The hollow square indicates the aquatic bryophyte cellulose data point included in the time series. The hollow circle indicates the 16.5-cm sediment cellulose value that was removed from the time series.

diamicton (Fig. 2). The magnetic susceptibility trends to lower values and the LOI to higher values upcore. The presence of large bryophyte macrofossils, which were abundant at various levels throughout the core, appears to be responsible for the LOI fluctuations. The generally high LOI (15–30%), low C/N ratios (11–12), and low bulk organic $\delta^{13}C$ (−27.5 to −28.5‰) all suggest that the organic matter in Meli Lake is primarily of aquatic origin (Meyers and Lallier-Verges, 1999). However, a peak in magnetic susceptibility and lower organic content at 16.5-cm depth is coincident with a 2-cm-thick unit of compact silty clay. The C/N ratio increases from 11 to 14, and the $\delta^{13}C$ increases by ∼2‰. Such trends in C/N ratios and $\delta^{13}C$ typically indicated greater proportions of terrestrially derived organic material within the sediments (Meyers and Lallier-Verges, 1999). This result is also consistent with the anomalously old radiocarbon date at 16.5 cm, which probably is from reworked terrestrial material.

Sediment cellulose $\delta^{18}O$ ranges from 17.5 to 21.0‰ and generally decreases upcore (Fig. 2). A high value at 16.5 cm is probably due to reworked terrestrial organic matter, and the data point was removed from the time series (Fig. 3). An aquatic bryophyte fragment found within the silt has a $\delta^{18}O$ value of 19.5‰. The cellulose $\delta^{18}O$ of aquatic bryophyte material is dependent on lake-water $\delta^{18}O$ and is included in the time series. Shifts in sediment cellulose $\delta^{18}O$, above and below 16.5 cm, are independent of any changes in the C/N ratio of $\delta^{13}C$.

We have chosen to limit our interpretation of sediment cellulose $\delta^{18}O$ to a qualitative assessment of trends for the past ∼8500 cal yr (Fig. 3). The time series is viewed as a qualitative proxy for lake-water $\delta^{18}O$ relative to the $\delta^{18}O$ value of the 2-cm sample. Although the imprecision of sediment cellulose analyses can be large relative to calcite $\delta^{18}O$, replicate analyses, as indicated by the error bars, show that the ∼2‰ decrease toward modern values is significant. The oxygen isotope composition of lake water has been inferred directly from the $\delta^{18}O$ values of sediment cellulose by subtracting DeNiro and Epstein's (1981) fractionation factor of 27 to 28‰ (±3‰) (MacDonald *et al.*, 1993; Wolfe *et al.*, 1996). However, it was not possible to use the same sediment cellulose relationship for the upper portion of the Meli core. The inferred lake-water $\delta^{18}O$ from the uppermost sample is −8.75‰, and the measured modern lake water is −17.52‰. Contrary to prediction, the measured lake water is also not significantly ^{18}O-enriched relative to the annual average $\delta^{18}O$ of precipitation in Barrow (−17.8‰), the nearest IAEA/WMO station (Rozanski *et al.*, 1993). Wolfe and Edwards (1997) similarly found that the $\delta^{18}O$ of single water-samples from a suite of Siberian lakes deviated more than expected from the $\delta^{18}O$ of water as inferred from sediment cellulose. Perhaps single water-samples do not reflect the average $\delta^{18}O$ of lake water during the thaw season. At a deep tundra lake, such as Meli Lake, seasonal variations in snowmelt input, seasonal overturn, weather conditions, and other related factors may significantly affect the $\delta^{18}O$ of a single sample.

The sediment cellulose $\delta^{18}O$ readings between ∼7000 and 8500 cal yr B.P. are more positive than modern (Fig. 3). Relative to core-top values, a general decrease to less positive $\delta^{18}O$ (lower than modern) occurs between ∼5000 and 7000 cal yr B.P. Decreased evaporation under wetter conditions would account for this trend. Moisture balance conditions were similar to modern between ∼2000 and 6000 cal yr B.P. The least positive values occur between ∼800 and 2000 cal yr B.P., indicating this period may have been particularly moist. The measurement from the aquatic bryophyte cellulose suggests a shift to drier conditions between ∼200 and 400 cal yr B.P.

Tangled Up Lake

From the base of the core upwards, the sedimentology of Tangled Up Lake begins with a transition from light gray clay with low organic carbon (0–2%) and carbonate (0–10%) to a section that has high organic carbon (15%) and carbonate (∼80%) at 340 cm (Fig. 4). Centimeter-scale measurements of $CaCO_3$ reflect the clay or silt laminations within the organic carbon and carbonate-rich sediment. A distinct high magnetic susceptibility zone occurs at 300 cm. The sediment is rich in organic carbon and carbonate and has been oxidized to a dark orange-brown color. At 275 cm, there is an abrupt shift to laminated silt, which is lower in organic carbon (5%) and carbonate (5–10%). Measurements of carbon and oxygen isotopes from the bulk calcite in this unit indicate that the carbonate is primarily detrital ($\delta^{18}O$ values range from −13.7 to −14.6‰ and $\delta^{13}C$ from 0.21

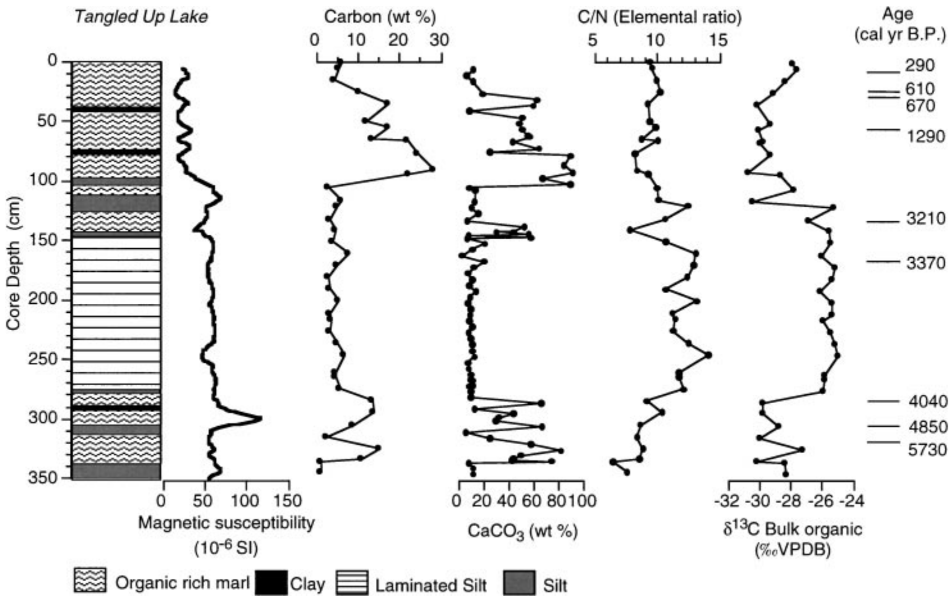

FIG. 4. Core lithology, physical properties, and geochemical properties including magnetic susceptibility, organic carbon, calcium carbonate, C/N ratio, and δ^{13}C of bulk sediment, and median calibrated radiocarbon ages from Tangled Up Lake.

to −1.2‰). At 145 cm, organic carbon (5–30%) and carbonate (10–90%) increase. These sediments are similar in composition and character to those below the laminated silt unit. This upper unit also includes centimeter-thick clay or silt laminae. Silty sediment between 115 and 125 cm contains little organic carbon or carbonate and lacks intact *Chara* stem casts.

The bulk organic data provides information regarding the source of organic matter (Fig. 4). The C/N ratio ranges from 6 to 15, which are typical values for aquatic organic material (Meyers and Lallier-Verges, 1999). The silty unit (120–275 cm) generally has higher values (12–14) than the sediments above and below (8–10). The δ^{13}C values of bulk organic matter are greater in the clastic units than in units rich in carbonate and organic carbon and steadily increase between 30 and 0 cm.

Calcite δ^{18}O are highly variable (−23.53 to −17.27‰) with shifts as large as 4.25‰ occurring over short (~10 cm) intervals (Fig. 5). In general, values are more negative than, or at times equivalent to, modern core-top values. *Chara* calcite was absent at 6, 12, 14, 18, 54, 56, and 58 cm.

The sediment cellulose δ^{18}O was contaminated by labile, interstitial water from clay minerals in the sediment matrix. Analyses were irreproducible, precluding paleoclimatic interpretation of these data (Anderson, 1999).

The δ^{18}O record from calcite shows century and possibly sub-century scale variability superimposed on a long-term trend of decreasing values from ~4600 to 50 cal yr B.P. (Fig. 5). A period of more positive values than present occurs between ~4000 and 4600 cal yr B.P. The calcite δ^{18}O is generally more negative relative to modern throughout the record, but it is particularly so between ~4600 and 6000 cal yr B.P. and between ~50 and 2300 cal yr B.P. The latter period is punctuated by numerous, brief periods of increased values. The most recent decrease between ~200 and 50 cal yr B.P. is followed by an increase to the present day.

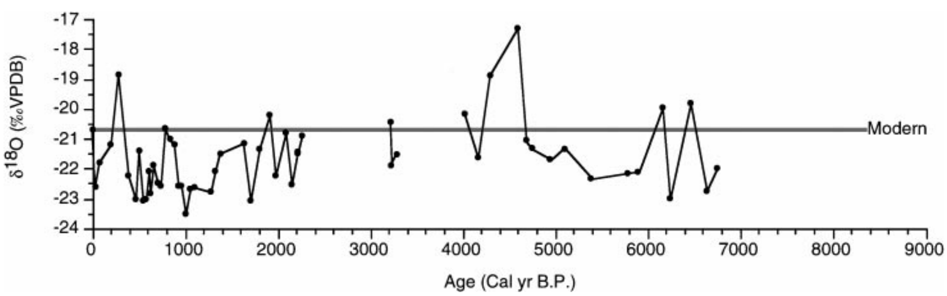

FIG. 5. Time series of Charophyte calcite δ^{18}O, Tangled Up Lake. Horizontal line is extended from the surface sediment value. Sample reproducibility is approximately ±0.5‰. The lack of data between 4000 to 3200 cal yr B.P. and 3100 to 2300 cal yr B.P. coincides with the silty laminated unit where no *Chara* calcite was found.

OXYGEN ISOTOPE INTERPRETATION

Meli Lake Sediment Cellulose

Changes in isotopic composition of Meli Lake and of the aquatic cellulose produced in that lake water is driven primarily by variations in effective moisture. This conclusion is based on the watershed characteristics of Meli Lake. Although nonclimatic factors could cause shifts in the Meli Lake sediment cellulose δ^{18}O, their influence was probably minimal. Contamination during analysis or by labile interstitial water within clay minerals in the sediment matrix are discounted on the basis of experiments performed during CO_2 extractions, reproducibility of analyses, and x-ray diffraction analysis that showed an absence of clay minerals (Anderson, 1999). Changing sources or proportions of aquatic and terrestrial material are inconsistent with the low C/N ratios and relatively depleted bulk-organic δ^{13}C values. The trends in sediment cellulose δ^{18}O have no systematic relationship with the bulk organic geochemical or sedimentological properties (Fig. 2). The proportion of aquatic material does not control changes in δ^{18}O, except in the 16.5 to 14.5 cm interval. However, the ^{18}O-enrichment of the aquatic bryophyte cellulose in this interval appears to be a reliable indicator of increased evaporative enrichment.

Tangled Up Lake Calcite

Tangled Up Lake is small relative to its watershed, and the lake-water oxygen isotope composition most likely reflects meteoric values. Modern lake water is −18.05‰, similar to the annual average δ^{18}O in Barrow (−17.8‰). Meteoric isotopic composition is strongly correlated with temperature at high latitudes. For middle and high latitudes, the average coefficient between δ^{18}O of atmospheric precipitation and mean annual surface temperature is ~0.6‰ per °C (Dansgaard, 1964; Rozanski *et al.*, 1992). The isotopic fractionation between calcite and lake-water temperature varies by −0.24‰ per °C. Combination of the aforementioned fractionation factors leads to an estimated coefficient of 0.36‰ per °C (Yu and Eicher, 1998).

For the past ~6900 cal yr B.P., the overall range of calcite δ^{18}O at Tangled Up Lake is 6‰ (Fig. 5), corresponding to a range of ~17°C in mean summer temperature. Existing paleovegetation and geomorphological data do not support such a large range, instead predicting ranges between 0 and 3°C (Calkin *et al.*, 1985; Anderson and Brubaker, 1994). Tangled Up Lake is small and shallow so that in this case coincident changes in rates of evaporation may account for the large calcite δ^{18}O shifts. For example, warm and dry conditions would tend to enhance evaporation, resulting in ^{18}O-enrichment. Conversely, cold and wet conditions would reduce evaporation resulting in ^{18}O-depletion. Warm-dry and cold-wet climates are the dominant summer synoptic patterns in the Brooks Range (Mock *et al.* 1998; Haugen, 1982). Furthermore, such synoptic patterns may be appropriate analogs for climatic conditions since 6000 cal yr B.P. (Edwards *et al.*, 2001).

HOLOCENE PALEOCLIMATE

Oxygen isotope data from this study show climatic variability at both century and millennial time scales. Trends described for the late Holocene are compatible with the glacial history of the Brooks Range and lake-level changes in interior Alaska (Fig. 6).

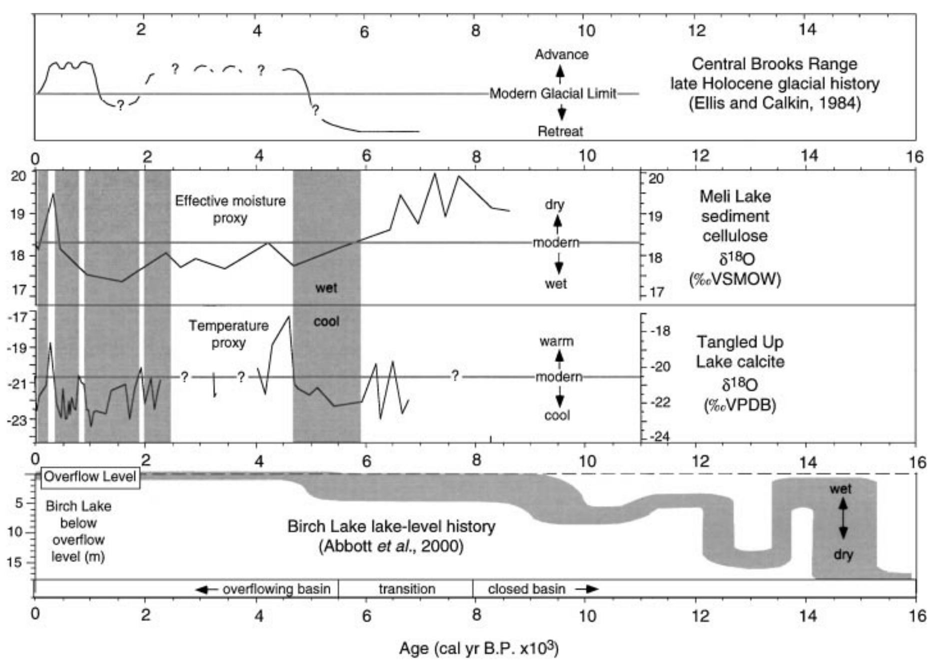

FIG. 6. Correlation of the central Brooks Range late Holocene glacial history, Meli Lake sediment cellulose δ^{18}O, Tangled Up Lake calcite δ^{18}O, and lake-level history from Birch Lake shown on a calibrated age scale. All radiocarbon ages were converted to calendar years using INTCAL98 (Stuiver *et al.*, 1998). Shaded blocks over both of the oxygen isotope time series indicate cooler and wetter conditions than present.

Furthermore, the combined records from Meli and Tangled Up lakes reveal changes in temperature and moisture balance at a higher temporal resolution for the middle to late Holocene than available from previous work. The new isotope records suggest that climate was drier than present between ~6000 and 8500 cal yr B.P., with alternating warm and cool intervals of ~200-yr-length. Between ~4600 and 6000 cal yr B.P., conditions were generally cooler than before, but the moisture balance increased to near-modern values. Moisture balance has been higher or similar to modern since 4600 cal yr B.P. A warm period between ~4000 and 4600 cal yr B.P. was followed by a trend toward cooler conditions, culminating at ~50 cal yr B.P. Brief warm intervals that are equivalent to or slightly cooler than modern are superimposed on this cooling trend. A warm period began at ~400 cal yr B.P. with maximum warmth by 200 cal yr B.P. The ^{18}O-enriched Meli Lake aquatic bryophyte cellulose, and the silty clay lithology suggest a decrease in effective moisture, an increase in eolian deposition, and a warm arid period centered at ~300 cal yr B.P. Temperatures steadily decreased until ~50 cal yr B.P. Since then, temperatures and moisture balance have increased to modern values.

Our data suggest glacial advances occurred between 4600 and 6000 cal yr B.P. and since 2200 cal yr B.P. Radiocarbon dating of late Holocene cirque deposits of the central Brooks Range suggests multiple glacial expansions since 1500 cal yr B.P. and possibly since ~5000 cal yr B.P. (Ellis and Calkin, 1984). Middle Holocene advances are dated by lichenometry with estimated precision of $\pm 20\%$ (Calkin, 1988). Hamilton (1986) interpreted episodes of alluviation and soil formation in the central Brooks Range to indicate glacial expansion between 2000 and 3500 cal yr B.P. and during the past 1200 to 1500 yr. Thus the results from Tangled Up and Meli lakes are consistent with these interpretations, both in terms of the timing and direction of climatic change (Fig. 6). These records indicate cooler conditions and increased effective moisture during periods of glacial advance. Rising lake levels at Birch Lake between ~7900 and 5500 cal yr B.P. correspond to times of increasing effective moisture at Meli Lake. The onset of permanently overflowing lake levels at Birch Lake by ~5500 cal yr B.P. is coincident with wetter than present conditions at Meli Lake, cooler conditions at Tangled Up Lake, and the onset of late Holocene glacial advances. After ~5500 cal yr B.P., Birch Lake overflowed and was insensitive to climatic change. In contrast, the oxygen isotope records from Meli and Tangled Up lakes provide detailed climatic histories from 5500 cal yr B.P. to the present.

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